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13. ABSTRACT (Maximum 200 words) This report results from a contract tasking University of Erlangen-Nuremberg as follows: The contractor shall investigate triangular arrays of Josephson tunnel junctions which have shown to be suitable for high frequency applications in the mm and sub-mm range. Yukon (AFRL) and Lin have designed an active antenna array based on 2D triangular arrays as oscillators. Synchronization between the oscillators (or sub-arrays) is provided by a phase shifter consisting of a parallel Josephson junction chain. The contractor has proposed an experiment based on a circuit made of two sub-arrays coupled by the phase shifter. Radiation from two sub-arrays will be coupled into a fin-line antenna and the emitted power will be studied as a function of a phase shift provided by the Josephson junction chain placed between the sub-arrays. Alternative methods using on-chip radiation detectors will be also explored.				
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Experiments with Mutually Coupled Arrays of Josephson Junctions*

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Chapter 1

Introduction

Yukon and Lin have proposed a design for an active antenna array based on 2D triangular arrays as oscillators. Synchronization between the oscillators (or sub-arrays) is provided by a phase shifter consisting of a discrete Josephson junction chain (1D-array). Numerical simulations have shown that, in a certain range of parameters, this circuit can enable radiation beam steering. In order to test the basic elements of this active antenna array, we have designed a circuit made of two sub-arrays coupled by a phase shifter. A double finline antenna has been designed in order to pick up radiation from the two sub-arrays. Here we present an outcome of our experiments and discuss the feasibility to use this circuit for rf applications

Chapter 2

Tests of the basic elements of the circuit

The realization of an active antenna array involves a rather complex circuit, in which several subarrays and phase shifters are connected through complicated bias schemes and control currents for the injection of the magnetic field. In addition to all this, an appropriate set of antennas has to be included in the circuit in order to pick up radiation. In the current design we have tested the basic elements of the circuit, in a simple bias configuration. The designed circuit is made of 2 subarrays coupled by a 1D-array used as a phase-shifter. In the following we give a short description of each individual element of the circuit and present results of measurement.

2.1 The subarray

The subarray consists of two rows of 13 cells, with *tabs* and resistors in the bias leads. A sketch of the array is shown in Fig. 2.1(a). Superconducting probes are placed across each row so that the individual row voltages can be measured.

The elementary cell contains 4 small Josephson junctions. The cell size is about $170\ \mu\text{m}^2$ and the junction size is about $9\ \mu\text{m}^2$. The critical current densities on 6 chips made by Hypres range between $1080\ \text{A}/\text{cm}^2$ and $1170\ \text{A}/\text{cm}^2$.

First, we have measured the insulated subarray, i.e. the array not coupled to phase shifter and antenna. The I - V curves show that the 2 rows have same parameters, such as critical currents, subgap resistances, normal resistances. Typical I - V curves at 4.2 K are shown in Fig. 2.2(a). Here the voltages of each row were measured. When we increase the temperature, so that the junctions have higher damping, and apply magnetic field, current steps appear and their voltage position is tunable by field. The two rows are locked at the same voltage along

the steps. Changing the magnetic field does not destroy this locked state. Families of I - V characteristics recorded while changing frustration between 0 and 1 show that at a given bias current the two rows are synchronized at the same voltage. Also, the changes of temperature were not destroying the voltage locking of the two rows. We have observed the step V_- at low voltages (up to 100 μV), the step V_+ (up to 180 μV), and another step at higher voltage (≈ 250 μV). The step V_+ is located at slightly lower voltage with respect to the previously measured 2 row arrays with the same cell size and approximately the same critical current density. The layout difference between these 2 row arrays and previously measured 2 row arrays is in the tabs used for bias. In the previous geometry the horizontal link of the tabs contained 2 junctions [Fig. 2.1(b)], while in the current geometry only a superconducting strip is present [Fig. 2.1(a)]. In order to compare the two arrays, in this layout we placed for reference also the array sketched in Fig. 2.1(b). The I - V curves of this array show that the step V_+ is at a voltage of about 200 μV for both rows. A typical I - V curve is shown in Fig. 2.3.

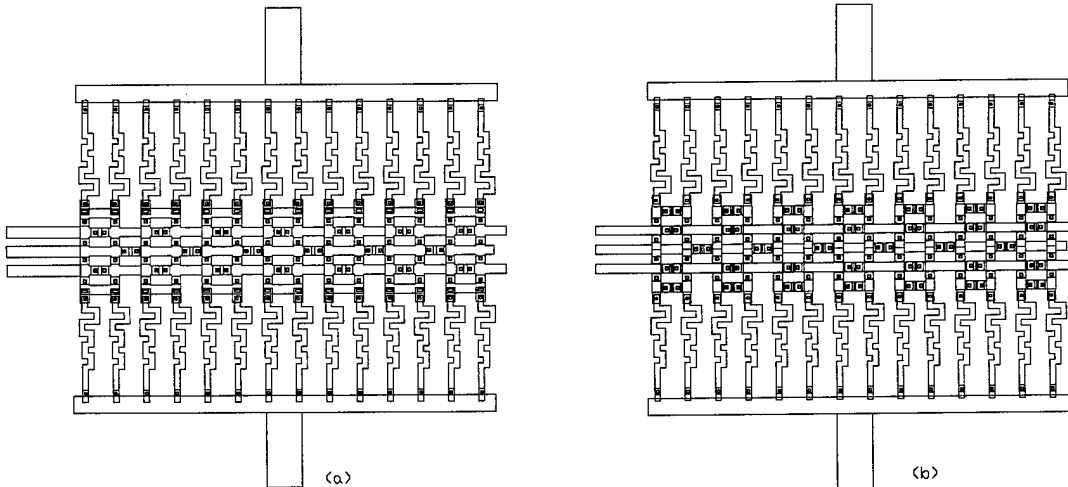


Figure 2.1: Layout of the subarray consisting of two rows of 13 cells. The elementary cell contains four junctions. For both arrays the cell size is about $170 \mu\text{m}^2$. The bias current flows through resistors and tab cells without horizontal junctions (a) and with horizontal junctions (b).

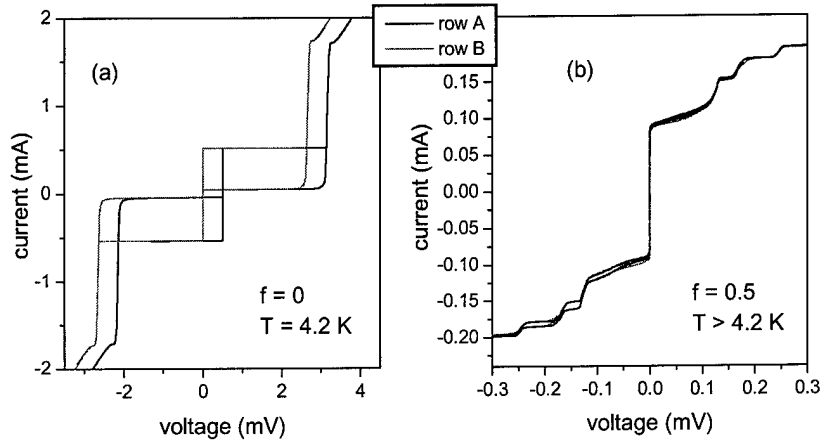


Figure 2.2: Typical I - V curves of the subarray sketched in Fig. 2.1(a). The voltages across the rows A and B are measured independently and for one row an offset of 0.5 mV is given in the voltage scale (a). An enlargement of the I - V curve measured at $f = 0.5$ (b). Due to higher damping at high temperature only a weak hysteresis remains in the I - V curve.

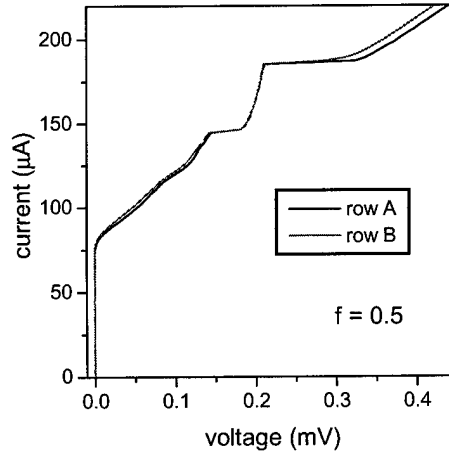


Figure 2.3: Typical I - V curves of the subarray sketched in Fig. 2.1(b). The voltages across the rows are measured independently.

2.2 The phase shifter

2.2.1 2 junction array

This phase shifter is sketched in Fig. 2.4(a). It is a parallel array of Josephson junctions which contains 14 cells. The elementary cell size is designed to be the same as the one of

the subarrays ($170 \mu\text{m}^2$) and it contains 2 junctions. The dependence of the array critical current vs. frustration shows a regular pattern, with approximately the same periodicity as measured in the case of the subarrays. In the presence of magnetic field the I - V curve shows a step whose voltage is tunable by field. The steps starts from zero voltage and at $f = 0.5$ it reaches its maximum value of $185 \mu\text{V}$. Figure. 2.5 shows the array critical current vs. the coil current ($\approx f$); relatively to the right axis, we report the voltage position of the step recorded at the bias point of $190 \mu\text{A}$.

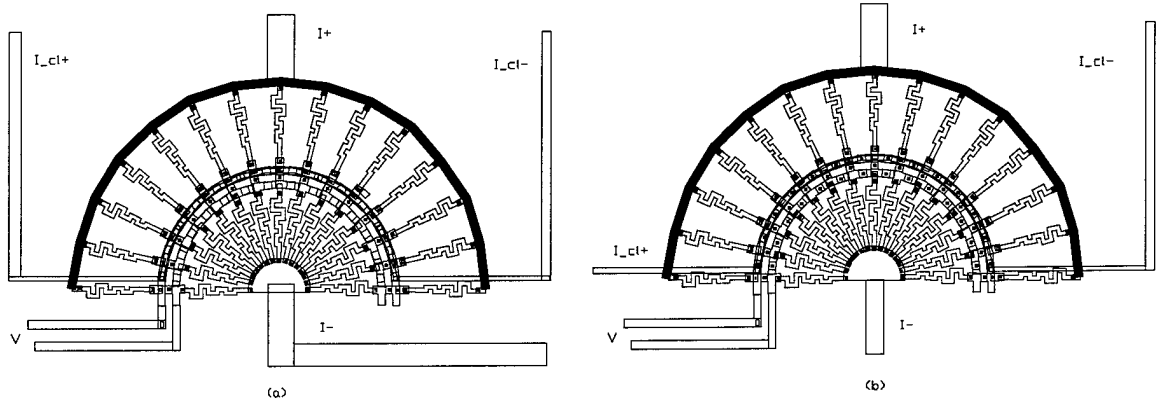


Figure 2.4: Layout of the semi-circular phase shifters consisting of 14 cells. The elementary cell contains either two junctions (a) or four junctions (b). A superconducting strip is placed along the phase shifter to allow passing a control current I_{cl} that induces the magnetic field.

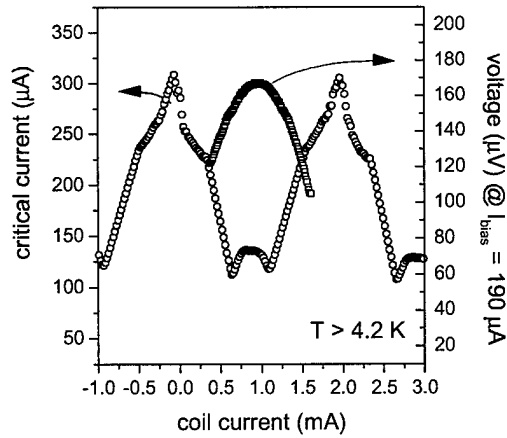


Figure 2.5: Array critical current vs. coil current (proportional to the applied magnetic field). Relatively to the right axis it is reported the voltage of the resonance.

2.2.2 4 junction array

The other type of phase shifter is sketched in Fig. 2.4(b). This phase shifter is exactly as the one described in the previous section, the only difference being that now the number of junctions per cell is 4. Thus, this phase shifter is designed to have the same cell resonance frequency ($f_{\text{res}} \propto 1/LC_{\text{tot}}$) as the subarray. Indeed, phase shifter and subarrays have the same cell size (which determines the inductance L) and the same number of junctions per cell ($C_{\text{tot}} = C/4$, where C is the single junction capacitance).

Note, that in the phase shifter with 2 junctions per cell, the absence of the *horizontal* junctions, *i.e.* of the junctions perpendicular to the direction of the bias current, prevents the fluxons from leaving the phase shifter from the top or bottom sides. Therefore, a better coupling between the subarrays can be achieved.

The tests of the insulated phase shifter with 4 junctions per cell have shown an I - V curve with asymmetric critical currents, as shown in Fig. 2.6(a). Due to this asymmetry, the resonances appear at different field values for the positive and negative bias [see Fig. 2.6(b)]. Also, the modulation of the positive and negative critical currents versus the applied magnetic field is not symmetric (see Fig. 2.7). This behavior does not depend on the vortices trapped in the array during the cooling below T_c . In the presence of magnetic field the I - V curve shows a step whose voltage is tunable by field. The step starts from zero voltage and at $f = 0.5$ it reaches its maximum value of about $80 \mu\text{V}$. At higher voltages ($\approx 200 \mu\text{V}$) there is another step, which is very unstable unless we work at temperatures very close to T_c .

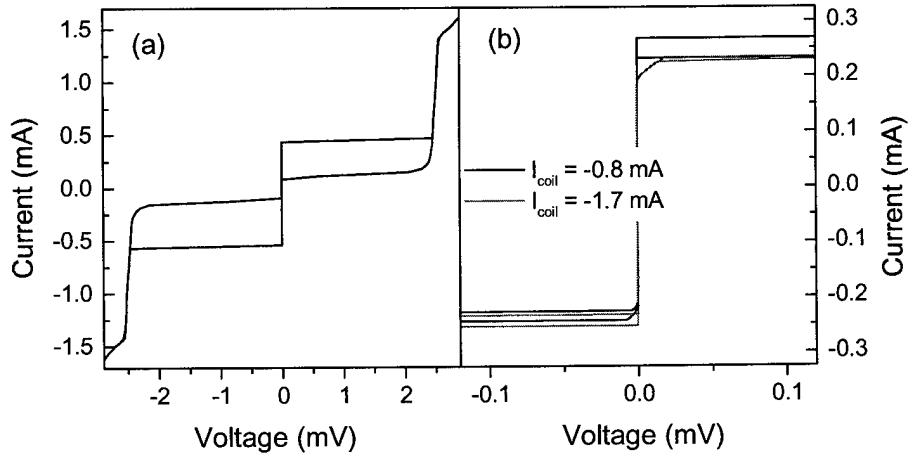


Figure 2.6: I - V curve of the phase shifter with 4 junctions per cell showing asymmetric critical currents (a); enlargement in the low voltage region for 2 different values of magnetic field.

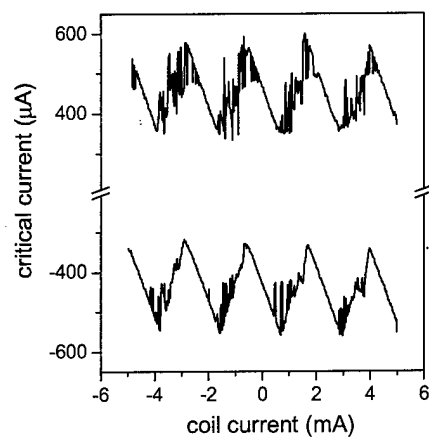


Figure 2.7: Measured dependences of the positive and negative critical current vs. coil current for the phase shifter with 4 junctions per cell.

Chapter 3

Description of the circuits and their characterization

3.1 Sample layout

The entire circuit with subarrays and phase shifter is shown in Fig. 3.1. The bias injection in the 2 subarrays is such that the fluxon chain exiting one subarray goes through the phase shifter and enters into the other subarray. Applying a local field to the semi-circular phase shifter would provide a phase gradient to keep synchronization between the fluxons in the 2 subarrays. Phase shifter and subarrays have to be at the same voltage state, *i.e.* the voltage across the phase shifter has to be equal to voltage across one row of the each subarray. In order to do so, we bias phase shifter and subarrays with a current proportional to the number of junctions in each device. Voltage probes allow to measure the voltage across each row of both the subarrays and across the phase shifter. The goals of our experiments were to study the emitted radiation as a function of a phase shift controlled by locally changing the field into the phase shifter, and to tune the phase of the oscillations in one subarray with respect to the other subarray. A double finline antenna [4] is placed by the side of the 2 subarrays. The antenna consists of two exponentially tapered electrodes which have a common ground also exponentially tapered. The two antennas are connected to the middle rows of the two subarray.

We have designed 3 types of circuits with antennas:

- **type A:** 2 subarrays coupled by the phase shifter consisting of 2 Josephson junctions per elementary cell. The phase shifter is placed at a distance of $3\text{ }\mu\text{m}$ from the subarrays.
- **type B:** 2 subarrays coupled by the phase shifter consisting of 2 Josephson junctions per elementary cell. From both sides, the semi-circular phase shifter is electrically connected

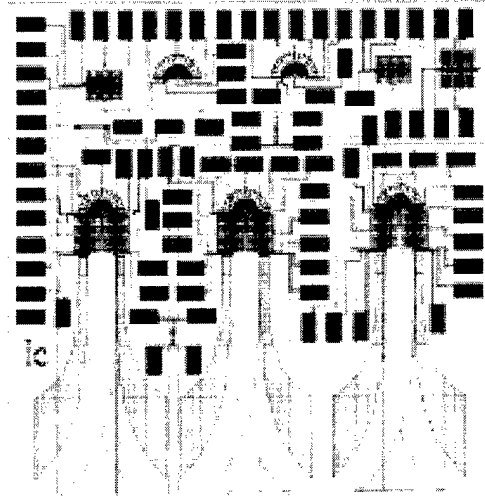


Figure 3.1: Layout of the whole chip (size $5 \times 5 \text{ mm}^2$).

to the edges of the 2 subarrays.

- **type C:** 2 subarrays coupled by the phase shifter consisting of 4 Josephson junctions per elementary cell. From both sides, the semi-circular phase shifter is electrically connected to the edges of the 2 subarrays.

In all 3 circuits the phase shifter is aligned (or attached) not directly to one of the row of the subarray, but to the biasing tabs. In this way one would expect less influence of the phase shifter on the current-voltage characteristic of the subarrays.

3.2 Results

We started with the characterization of the circuit **type A**, *i.e.* the 2 subarrays coupled non galvanically to the phase shifter with 2 JJ's per cell. First, we have chosen a bias configuration through one of the subarray only, in order to test the emission properties through the double finline antenna and the performance of the antenna itself. Coupling an array to a double finline antenna is for us a new design never tested before.

In order to check the antenna operation, we externally applied rf power generated by a Gunn diode oscillator (with a center frequency of 89.75 GHz). By doing this, we were irradiating the subarray through the double finline antenna and recording the I - V curves. An attenuator was used between the Gunn oscillator and the waveguide input. Under the effect of rf power, Shapiro steps and photon assisted tunneling steps were induced on the

array I - V curves. The same type of experiments, using the same frequency and rf amplitude, has been performed on another array coupled by our conventional single finline antenna successfully tested in our previous experiments. Comparisons of the amplitude of the induced effect on the I - V curves have shown that the new double finline antenna has by about 8 ± 2 dB larger insertion loss than the single finline antenna. Due to the reduced performance of the antenna, we had not succeed to observe any radiation in our standard broad band setup for 80-120 GHz. In order to increase the sensitivity of radiation measurements, we used the rf circuit as sketched in Fig. 3.2. The signal coming from the array was fed into the input of

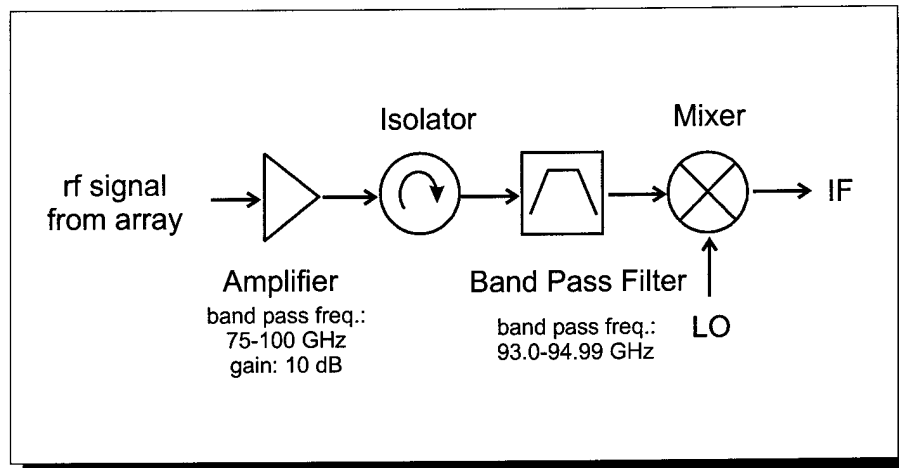


Figure 3.2: Block diagram of the modified low-noise setup for 93-95 GHz radiation measurements.

a low noise amplifier, designed for the frequency range of 75-100 GHz with a gain of 10 dB and a noise figure of 5 dB at 95 GHz. The amplified signal goes to an isolator, needed to avoid interference between the mixer and the pre-amplifier (without the isolator the amplifier was self-excited and Shapiro steps were observed in the I - V curve of the array). Behind the amplifier we used a band pass filter, with a band of 93.06-94.99 GHz. With this new set up, we have been able to observe radiation from a single sub-array. Typical measurements data are shown in Fig. 3.3.

We have tried to measure radiation when both sub-arrays are biased (sample KL230C#5). The bias current was flowing in the same direction in the two subarrays and the 4 voltages across each individual row were monitored. Unfortunately, in this case, no radiation have been recorded, in the whole band pass of the filter. The major difficulty was in locking the 2 subarrays at the same voltage. We have tried to do this both by means of magnetic field and of temperature, but without success. We have repeated the experiment in a different bias

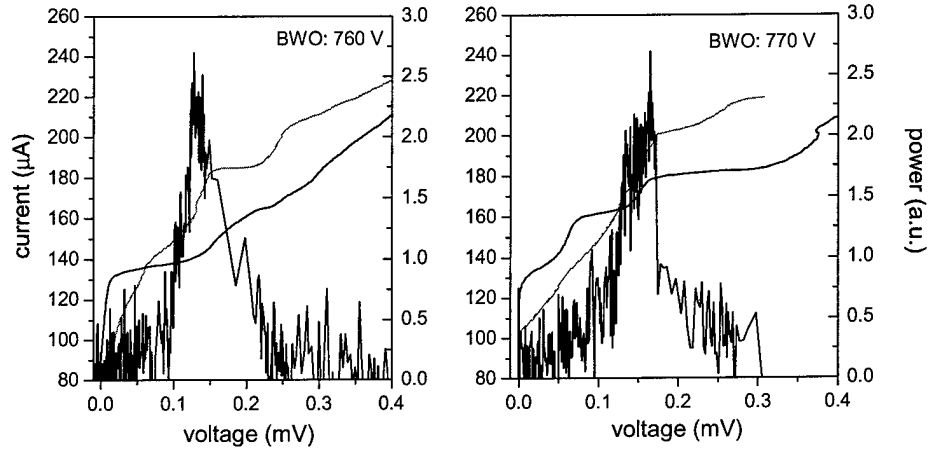


Figure 3.3: Current-voltage curves of a double row array and radiation output detected with the double finline antenna, at 2 different frequencies of the local oscillator. Gray and black curves refer to the voltage across each row.

configuration, when the direction of the bias current is opposite in the 2 subarrays, and still did not get any measurable radiation.

In the array **type B** the phase shifter is electrically coupled to the 2 subarrays. First, we measured the combined circuit without phase shifter. The bias current passes through the 2 subarrays, and we performed measurements both for the same direction and opposite directions of the bias. We have systematically observed that the 2 subarrays have dissimilar critical currents. An example is shown in Fig. 3.4, though this tendency of having unequal rows was observed at various temperatures and fields, and in all measured samples. Moreover, as we could measure the voltages row by row, we have observed that always the inner rows, *i.e.* the rows which have nearby the connection to the phase shifter, had a lower critical current. In some cases we could make the rows operate at the same frequency, but still we have never observed any measurable radiation.

In order to have the same current source for both the sub-arrays rays and the phase shifter, we have used a current splitter which allowed to tune in independent way the current in the two subarrays and the current in the phase shifter. This allowed to get the same voltage states in all 3 devices. Also in this case, we have not been able to see radiation coming out from the combined circuit.

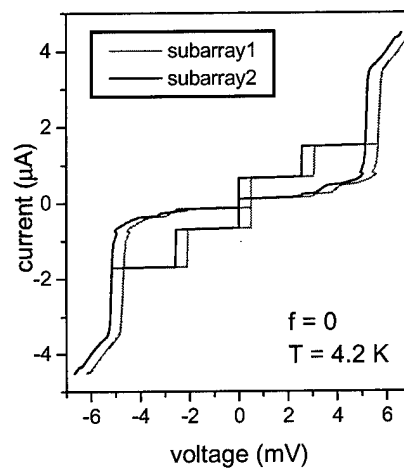


Figure 3.4: Current-voltage curves of 2 double row arrays biased in series (sample 230B#5). Gray and black curves refer to individual subarrays, the voltage of which is measured across the 2 rows. An offset of 0.5 mV is applied to the second curve.

Chapter 4

Conclusion

We have designed and tested circuits based on 2 row arrays of Josephson junctions mutually coupled by a phase shifter. The phase shifter consisted of a parallel array of junctions. In order to be able to pick up radiation from both sub-arrays, a double finline antenna with exponentially tapered electrodes has been designed and tested. All elements of the circuit have been tested individually, and their dc properties have been characterized in the presence of magnetic field and at various temperatures. Comparative measurements between two types of phase shifters (with and without horizontal junctions) and sub-arrays (bias tabs with and without horizontal junctions) have been performed. Radiation emitted through the double finline antenna has been observed when only one of the sub arrays was biased, while the other remained not active.

Several points still remain to be clarified. First, it might be important to better understand the role of the bias tabs in the 2 row arrays. Our data show that, in the case of the array with horizontal junctions in the tabs, the $V+$ resonance in the I - V characteristics is more stable. Second, it remains not clear why the arrays galvanically coupled to the phase shifter show always different critical currents from row to row. In addition, the rows never lock to the same voltage.

We have measured higher insertion losses in the double finline antenna with respect to our conventional finline antenna. The performance of the new antenna might be improved, for example by changing the profile of the exponentially tapered electrodes, and extending the ground plane (ground electrode of the antenna) under the arrays. It would be better first to characterize the new antenna with one of the earlier and well established array designs.

In order to simultaneously control several voltages, the developed layout contains many overlapping leads, which tend to pick up the internal and external interference as well as introduce additional noise into the system. The control line used to create a local field in

the phase shifter was affecting also the sub array, whose critical current was responding to changes of current in the control line. The circuit has shown very little tolerance with respect to the spread of parameters. In addition, the stability of the steps was very poor. Sometimes, consecutive sweeps of the I - V curves, while keeping constant the parameters such as temperature and frustration, were showing different steps. We suppose this behavior to be due to redistribution of magnetic flux in this complicated layout with overlapping leads.

In summary, we have designed and individually tested new elements such as the subarrays, phase shifters and double finline antenna. Final realization of the integrally operating circuit of subarrays with a tunable phase shift is a rather difficult task that still remains unsolved.

Acknowledgment

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